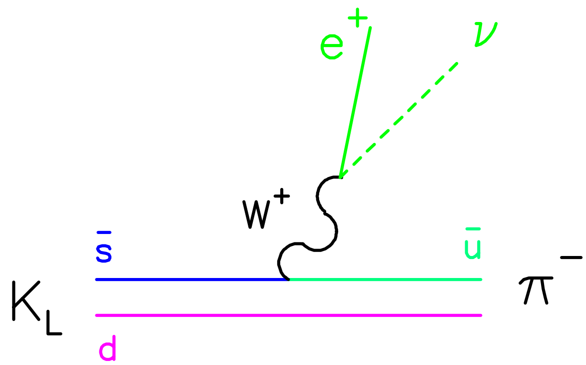
Rare Kaon Decay Searches

L. Littenberg - BNL

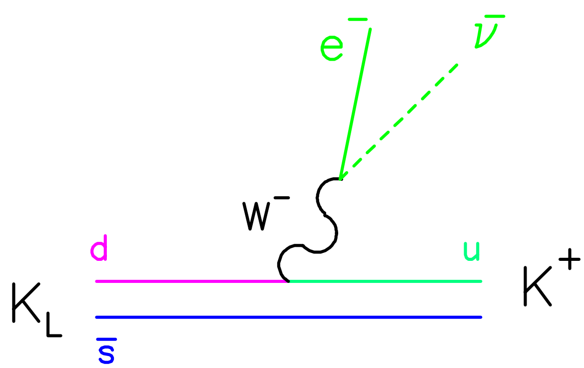
KAON 2001, 16 June 2001

What makes decays rare?

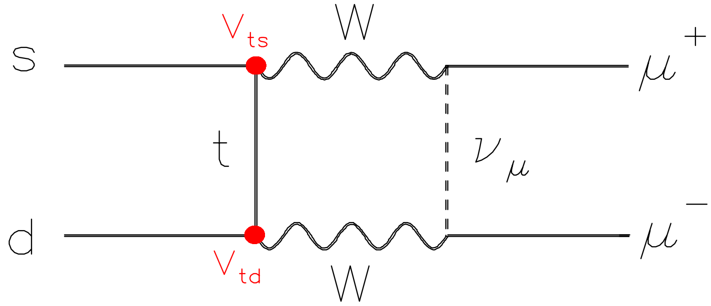
Common decay:



Rare by virtue of kinematics:



Rare since suppressed to 2nd order:



Rare K decay modes studied recently

$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \mu^+ \mu^-$
$K^+ \to \pi^+ \mu^+ \mu^-$
$K_L \to \mu^+ \mu^-$
$K^+ \to \pi^+ e^+ e^- \gamma$
$K_L \to e^\pm e^\mp \mu^\pm \mu^\mp$
$K_L \to \pi^+ \pi^- \gamma$
$K^+ \to \pi^+ \pi^0 e^+ e^-$
$K_L \to \pi^0 \gamma\gamma$
$K^+ \to \mu^+ \nu \gamma$
$K^+ \to \mu^+ \nu e^+ e^-$
$K_L \to e^+ e^- \gamma$
$K_L \to e^+ e^- \gamma\gamma$
$K_L \to e^+ e^- e^+ e^-$
$K^+ \to \pi^+ \mu^+ e^-$
$K_L \to \mu^\pm e^\mp$
$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^+ X^0$
$K^+ \to \pi^+ \gamma$

$K_L \to \pi^0 \nu\bar{\nu}$
$K_L \to \pi^0 e^+ e^-$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to e^+ e^-$
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$
$K^+ \to \pi^+ \pi^0 \gamma$
$K_L \to \pi^+ \pi^- e^+ e^-$
$K^+ \to \pi^0 \mu^+ \nu \gamma$
$K^+ \to \pi^+ \gamma\gamma$
$K^+ \to e^+ \nu e^+ e^-$
$K^+ \to e^+ \nu \mu^+ \mu^-$
$K_L \to \mu^+ \mu^- \gamma$
$K_L \to \mu^+ \mu^- \gamma\gamma$
$K_L \to \pi^0 e^+ e^- \gamma$
$K_L \to \pi^0 \mu^\pm e^\mp$
$K^+ \to \pi^- \mu^+ e^+$
$K^+ \to \pi^- \mu^+ \mu^+$
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$

Motivation for Rare K Decay Experiments

Forbidden

S.M. forbids (or greatly inhibits) many kinematically possible modes

A number of these are allowed (or enhanced) by alternative approaches

Accessible sensitivity to these processes corresponds to very high mass scales

Discouraged

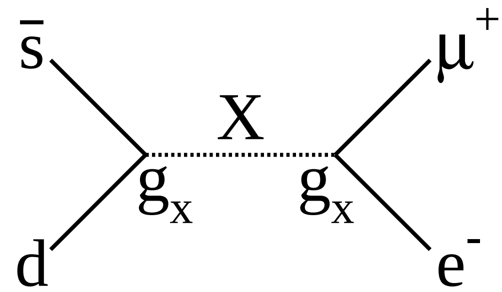
Certain very inhibited processes cleanly sensitive to S.M. parameters

Tolerated

Suppressed processes are a good area for testing chiral perturbation theory and other approaches to understanding the low energy structure of the S.M.

Lepton Flavor Violation

Poster child for sensitivity to BSM processes such as $\rightarrow$ Attainable sensitivity corresponding to $M_X \gtrsim 100$TeV, clean signatures



Current status:

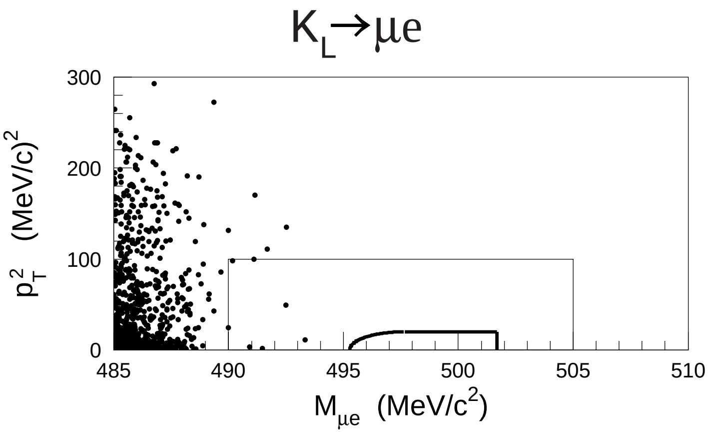
Process	90% CL Limit	Experiment	Reference
$K_L \rightarrow \mu e$	4.7×10^{-12}	AGS-871	PRL 81:5734
$K^+ \rightarrow \pi^+\mu^+e^-$	2.8×10^{-11}	AGS-865	PRL 85:2450
$K^+ \rightarrow \pi^+\mu^-e^+$	5.2×10^{-10}	AGS-865	PRL 85:2877
$K_L \rightarrow \pi^0\mu e$	4.4×10^{-10}	KTeV	Bellantoni/Moriond

More $K^+ \rightarrow \pi^+\mu^+e^-$ and $K_L \rightarrow \pi^0\mu e$ data under analysis.

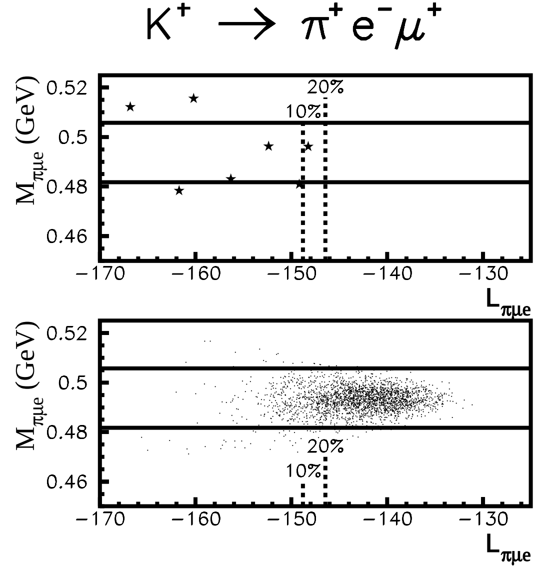
A long list of BSM theories predict LFV in K decays at some level, e.g. extended technicolor, SUSY, heavy neutrinos, horizontal gauge bosons, etc. Also necessary to study both two and three body decays to check Lorentz structure of any new interaction, generation number sensitivity, etc.

But these experiments have already helped kill the most promising approaches that predicted finite effects. Now theorists predicting more accessible levels of LFV in rare muon processes.

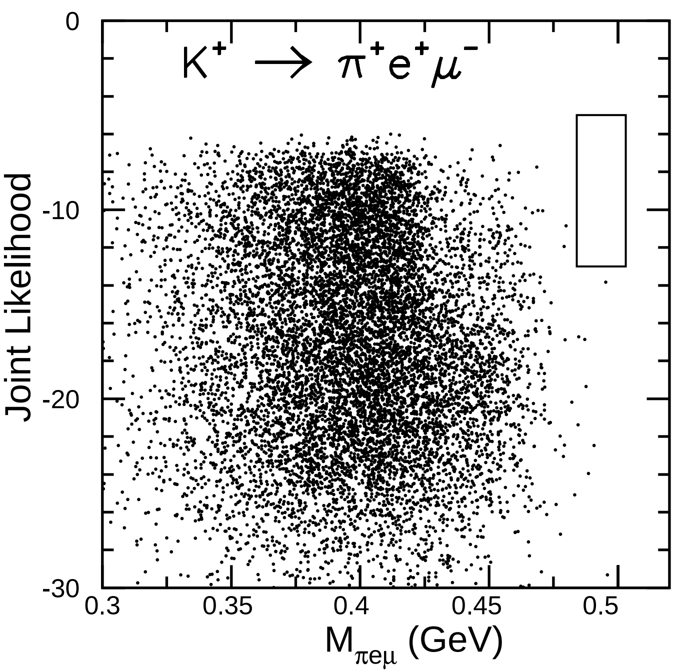
Future progress on LFV in kaon decays likely to be slow. No dedicated experiments on the horizon, and background getting harder to fight.



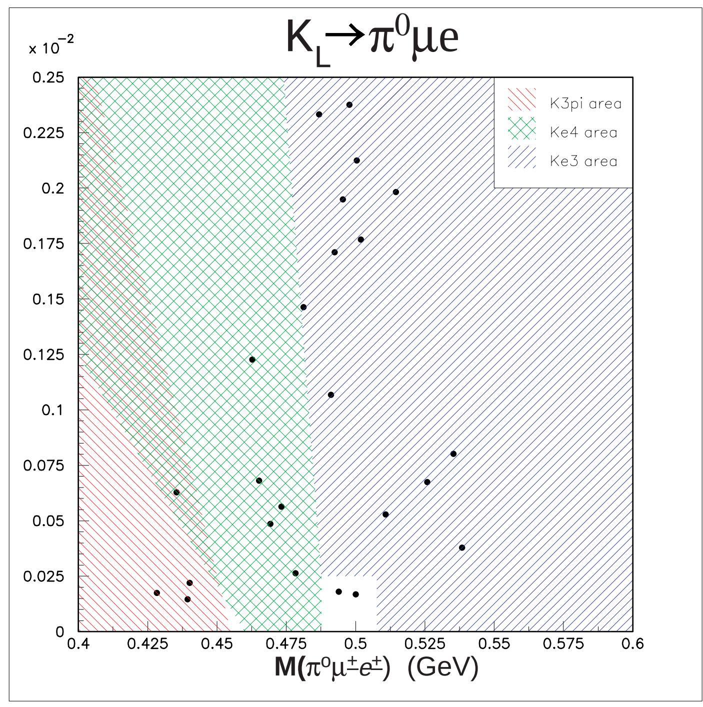
$K_L \to \mu e$
p_T^2 (MeV/c)^2
$M_{\mu e}$ (MeV/c^2)



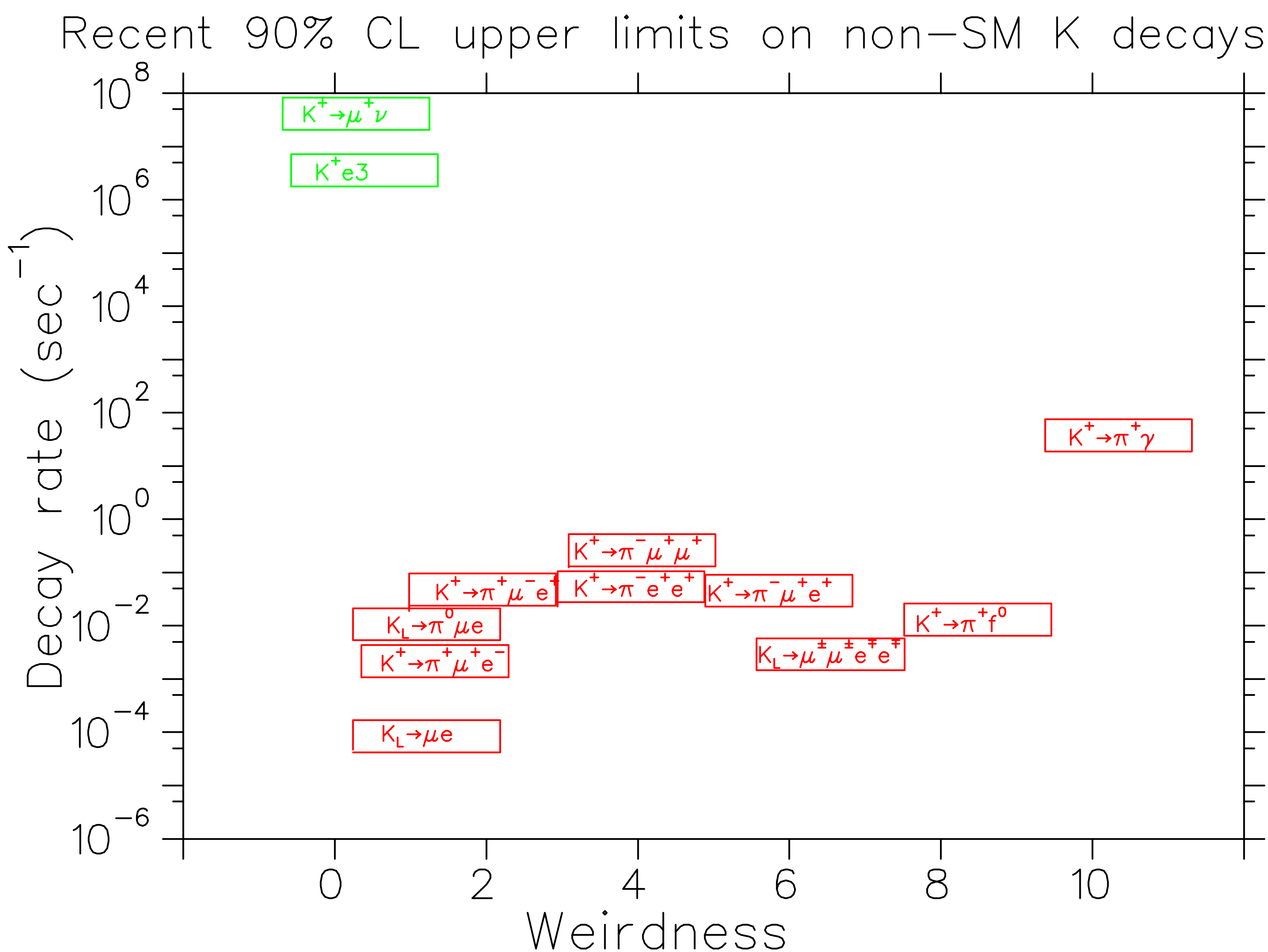
$K^+ \to \pi^+ e^- \mu^+$
$M_{\pi\mu e}$ (GeV)
$L_{\pi\mu e}$
20%
10%



$K^+ \to \pi^+ e^+ \mu^-$
Joint Likelihood
$M_{\pi e\mu}$ (GeV)



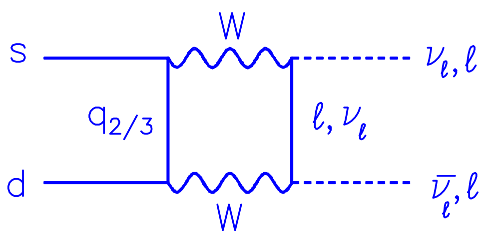
$K_L \to \pi^0 \mu e$
x 10^{-2}
K3pi area
Ke4 area
Ke3 area
$P_\perp^2$ (GeV)^2
$M(\pi^0\mu^\pm e^\pm)$ (GeV)

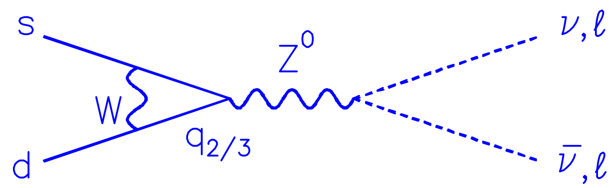


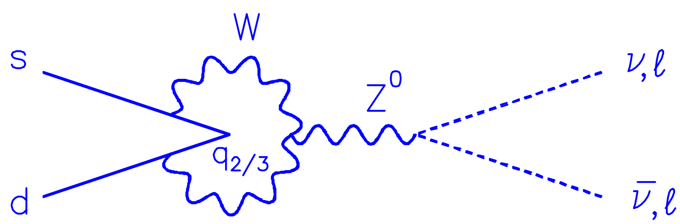
Recent 90% CL upper limits on non−SM K decays
Decay rate (sec^{-1})
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
0
2
4
6
8
10
Weirdness
$K^+ \to \mu^+ \nu$
$K^+ e3$
$K^+ \to \pi^+ \gamma$
$K^+ \to \pi^- \mu^+ \mu^+$
$K^+ \to \pi^+ \mu^- e^+$
$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^- \mu^+ e^+$
$K_L \to \pi^0 \mu e$
$K^+ \to \pi^+ f^0$
$K^+ \to \pi^+ \mu^+ e^-$
$K_L \to \mu^\pm \mu^\pm e^\mp e^\mp$
$K_L \to \mu e$

One-loop K Decays

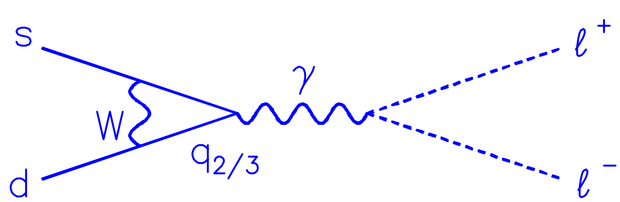
Short-distance contributions to K decays. These decays include $K_L \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+\mu^-$, etc. The hadronic matrix elements involved are known from common decays such as $K^0 \to \pi^+ e^- \bar{\nu}$. These contributions can be cleanly calculated in terms of m_t, m_c and the product of CKM elements $V_{ts}^* V_{td} \equiv \lambda_t$.



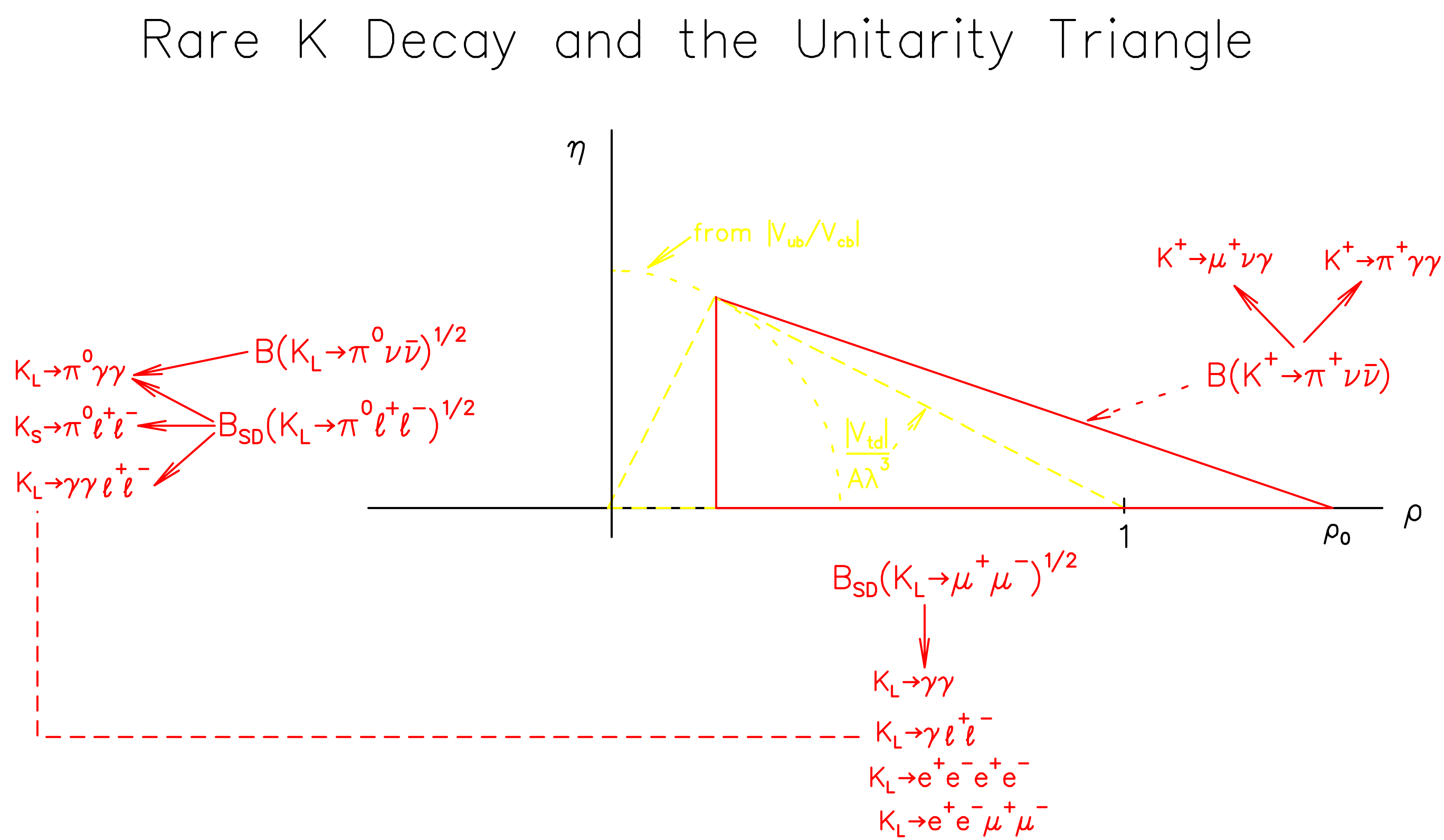




But there's a Murphy's Law for these processes:
The same interactions that allow charged final state leptons to be detected, mediate long-distance contributions. E.g.:



To avoid this one must exploit decays containing a $\nu\bar{\nu}$ pair.



Rare K Decay and the Unitarity Triangle
η
ρ
1
ρ0
from |Vub/Vcb|
|Vtd|/Aλ3
B(KL→π0νν̄)1/2
KL→π0γγ
BSD(KL→π0ℓ+ℓ−)1/2
KS→π0ℓ+ℓ−
KL→γγℓ+ℓ−
K+→μ+νγ
K+→π+γγ
B(K+→π+νν̄)
BSD(KL→μ+μ−)1/2
KL→γγ
KL→γℓ+ℓ−
KL→e+e−e+e−
KL→e+e−μ+μ−

$\underline{K_L \to \mu^+\mu^-}$

The short distance part of $B\left(K_L \to \mu^+\mu^-\right)$ given by:

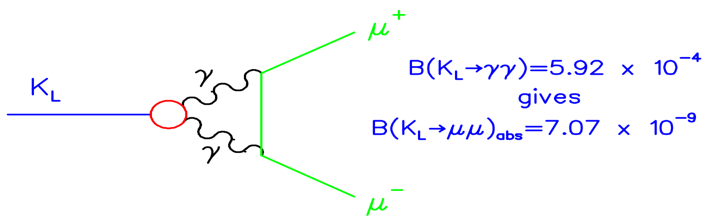
$$B^{SD}_{\mu\mu} = \frac{\tau_{K_L}\alpha^2 B_{K^+\mu\nu}}{\tau_{K^+}V^2_{us}\pi^2 sin^4\theta_W}\left[Re\left(\lambda_c\right)Y_{NL} + Re\left(\lambda_t\right)Y\left(x_t\right)\right]^2 \approx \mathcal{O}\left(10^{-9}\right)$$

where $Re\left(\lambda_c\right) = \lambda\left(\frac{\lambda^2}{2} - 1\right)$; $\lambda \equiv sin\theta_{Cabibbo}$

To a good approximation $Y\left(x_t\right) = 0.32\left(m_t/m_W\right)^{1.56}$

$Y_{NL} \approx 3 \times 10^{-4}$

But this is dominated by an absorptive contribution from:



much larger than the dispersive part.

Data now precise enough (2.4%), this can be meaningfully subtracted:

$(7.18 \pm 0.17) \times 10^{-9} - (7.07 \pm 0.18) \times 10^{-9}$

$\Rightarrow \quad B\left(K_L \to \mu^+\mu^-\right)_{dispersive} < 0.37 \times 10^{-9}$ @ 90%CL

But there is also a long distance contribution to the real part
This can interfere with the short distance contribution
To untangle, must know $A\left(K_L \to \gamma\gamma\right)$ with γs off mass-shell
- size, calculability controversial

Can we **measure** this?

There are recent results on:

$K_L \to ee\gamma$	NA48
$K_L \to \mu\mu\gamma$	KTeV
$K_L \to eeee$	KTeV, NA48
$K_L \to ee\mu\mu$	KTeV, NA48

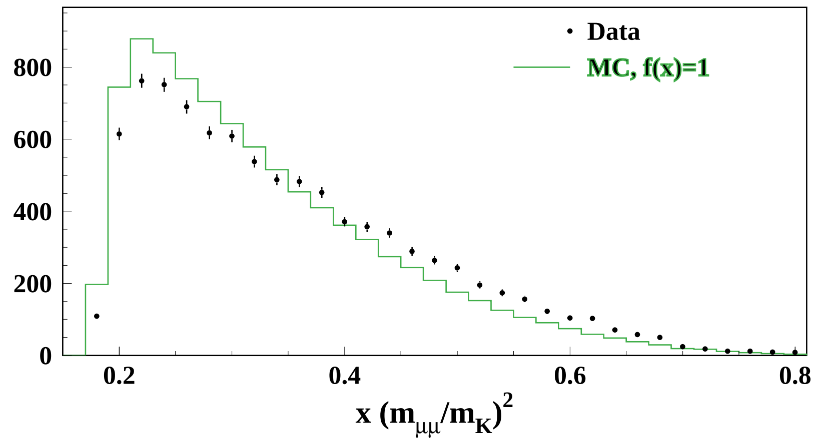
People have used fits to some of these to put a limit on ρ,
- how legitimate this is is still unclear

Virtual photon form factors

Virtual photon form factors are needed to calculate the long-distance dispersive contribution to $K_L \to \mu^+\mu^-$.

That these processes not pointlike, now clear:

Data at right from KTeV $m_{\mu\mu}$ dist. in $K_L \to \mu^+\mu^-\gamma$

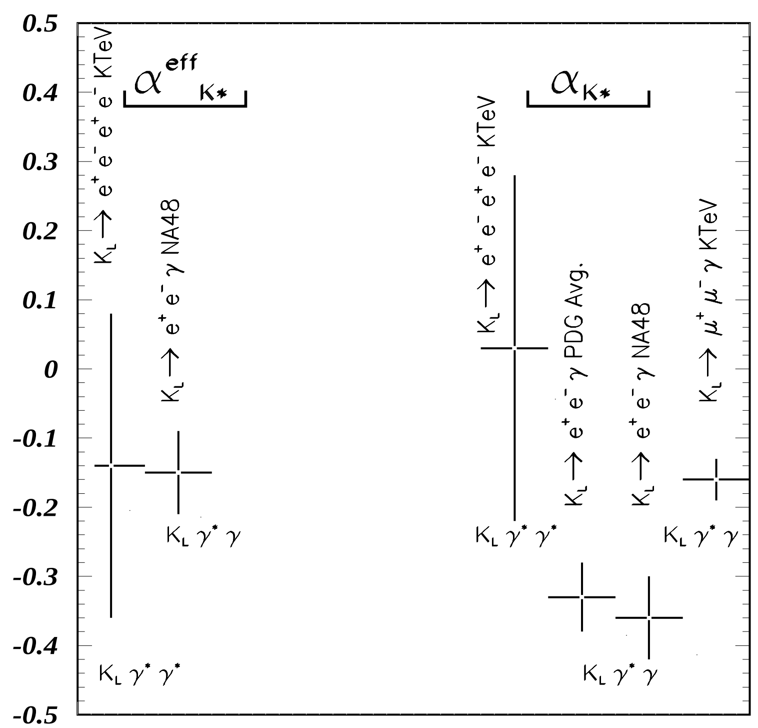


There are a couple of form factor parameterizations on the market; a popular one is Bergström, Massó, & Singer (BSM), with parameter α_{K^*}

Figure at right shows α_{K^*} from recent experiments. (From E. Halkiadakis thesis)

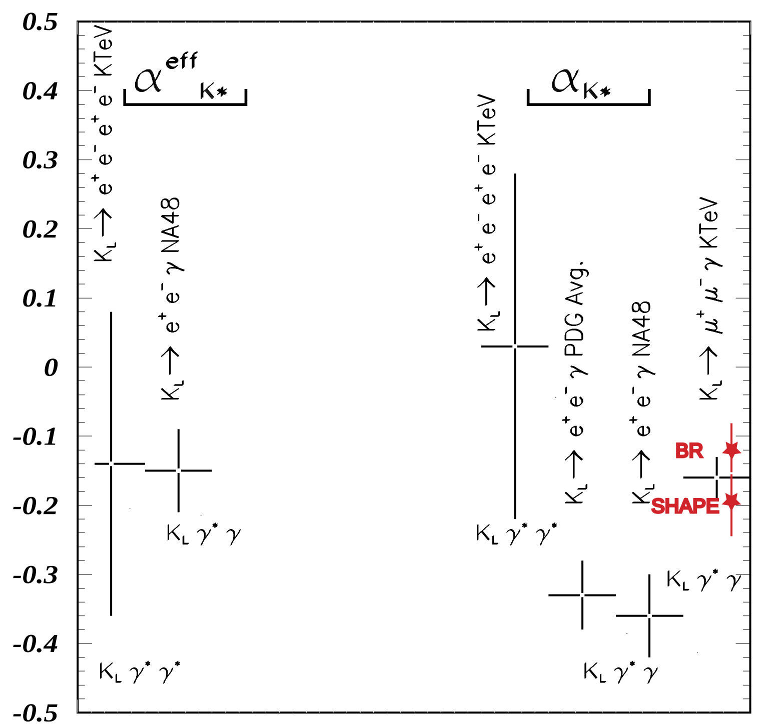
Agreement not inspiring

+ some issues not apparent in figure



Finally, different parameterizations give different results, *e.g.* from KTeV $K_L \to \mu\mu\gamma$:

$$|ReA_{LD}^{BMS}| < 3.6 \times 10^{-5} \text{ but } |ReA_{LD}^{DIP}| < 2.07 \times 10^{-5}$$



0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
α^{eff}_{K*}
α_{K*}
$K_L \rightarrow e^+e^-e^+e^-$ KTeV
$K_L \gamma^* \gamma^*$
$K_L \rightarrow e^+e^-\gamma$ NA48
$K_L \gamma^* \gamma$
$K_L \rightarrow e^+e^-e^+e^-$ KTeV
$K_L \gamma^* \gamma^*$
$K_L \rightarrow e^+e^-\gamma$ PDG Avg.
$K_L \rightarrow e^+e^-\gamma$ NA48
$K_L \gamma^* \gamma$
$K_L \rightarrow \mu^+\mu^-\gamma$ KTeV
$K_L \gamma^* \gamma$
BR
SHAPE

$\underline{K \to \pi\nu\bar{\nu}}$

$$B\left(K^+ \to \pi^+\nu\bar{\nu}\right) \quad \propto B\left(K^+e3\right) \; \sum_l |\lambda_c X_{NL}^{\ell} + \lambda_t X\left(x_t\right)|^2 \approx 8 \times 10^{-11}$$

$$B\left(K_L \to \pi^0\nu\bar{\nu}\right) \quad \propto B\left(K^+e3\right) \; \sum_l \left(Im\lambda_t X\left(x_t\right)\right)^2 \approx 3 \times 10^{-11}$$

$$X\left(x_t\right) \approx 0.66 \left(m_t/m_W\right)^{1.15}$$

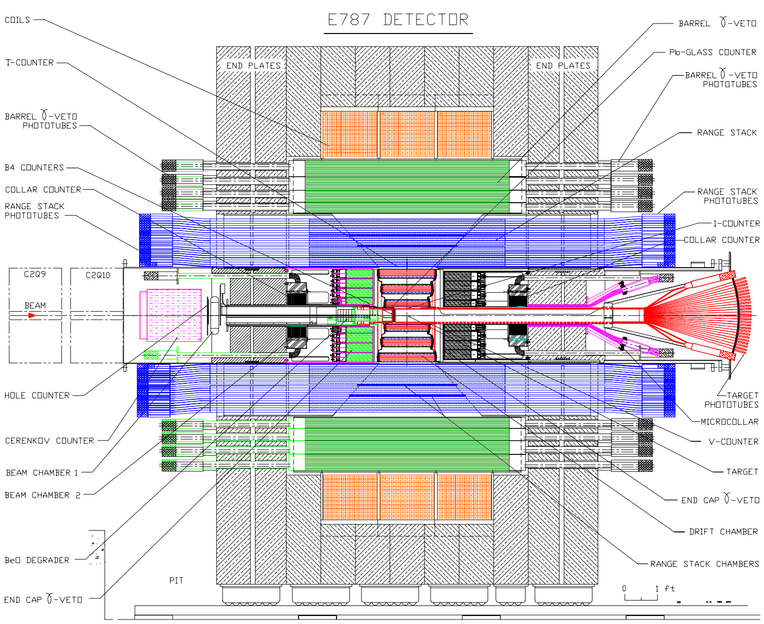
Intrinsic theoretical uncertainty on K^+ mode a few %
Intrinsic theoretical uncertainty on K_L mode $\sim 2\%$

In leading order in Wolfenstein variables K^+ gives a circle and K_L gives a height in the complex plain (i.e. η)

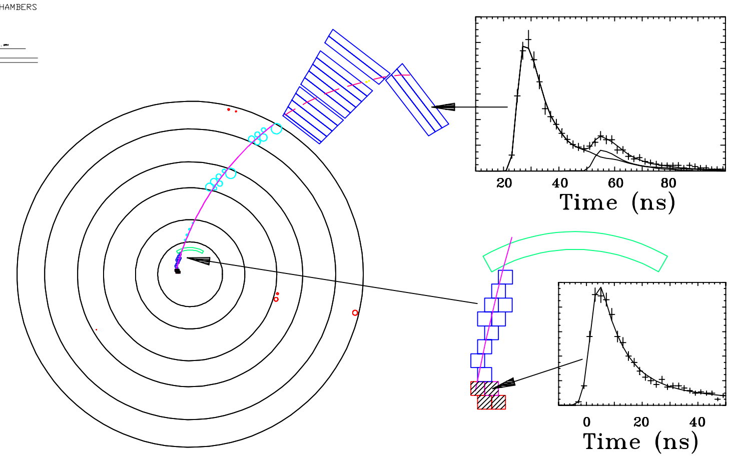
I prefer to leave them in terms of $\lambda_t \equiv V_{ts}^* V_{td}$

Theoretically golden, experimentally very challenging

E787



First event in 1995 data set:



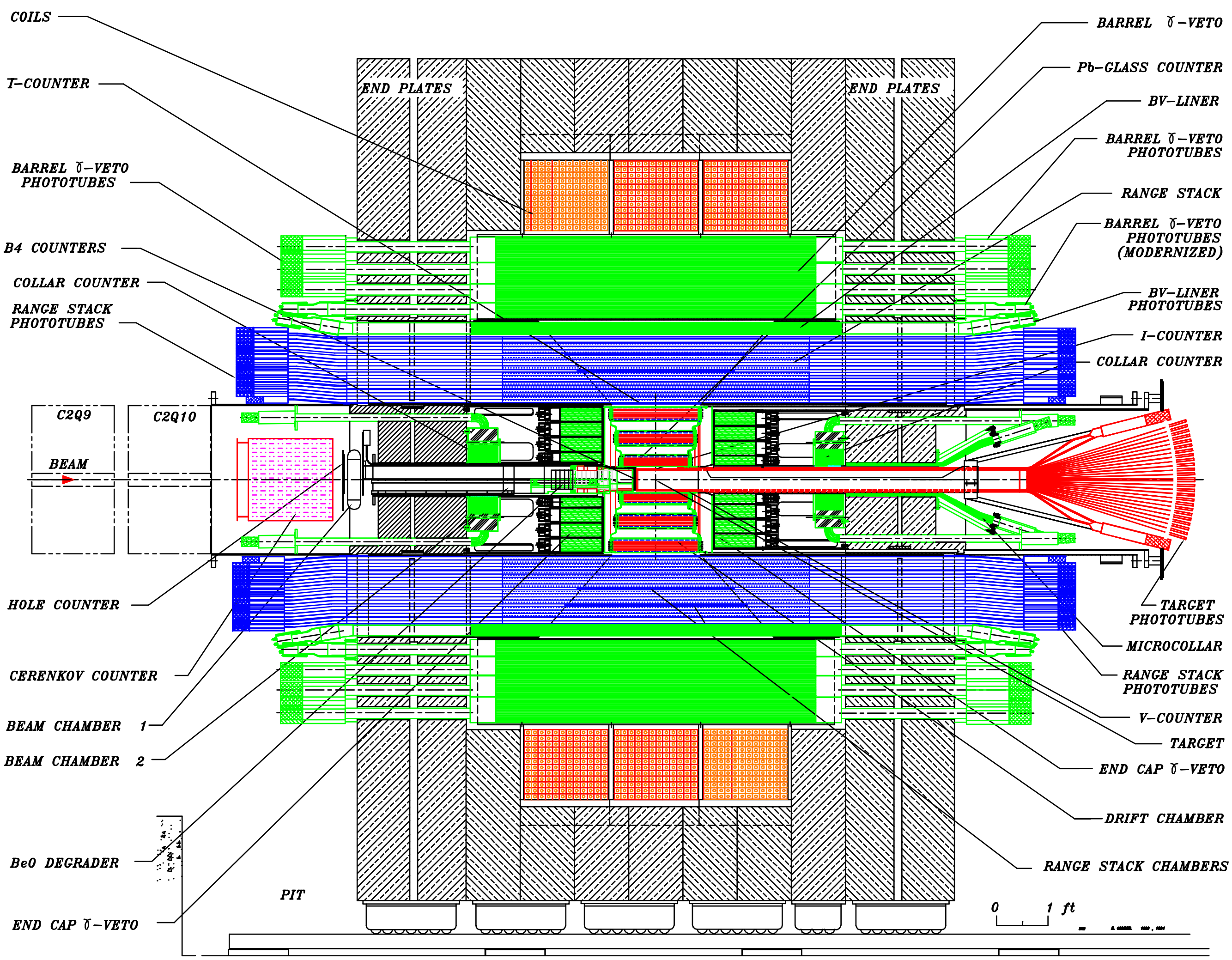
1995-7 data set still had only 1 event, with bckgnd < 0.1 evts.

$$B(K^+ \to \pi^+ \nu \bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10} \ (\sim \text{twice SM}).$$

1998 data set $\approx$ to all previous E787 data
- background very similar to that of 1995-7

Stay tuned!

E949 Measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$



Upgrade of BNL AGS 787

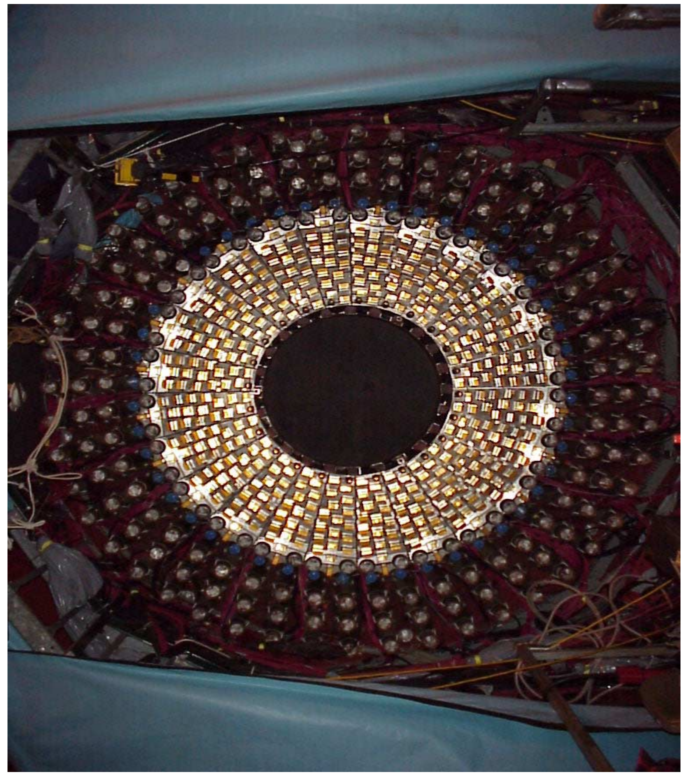
Sensitivity improvement with respect to E787 (1995):

- Increased spill length ($\times 1.56$)
- Lower momentum ($\times 1.38$)
- Increased efficiency (trigger, DAQ, analysis) ($\times 3.2$)
- Acc. below $K\pi 2$ + higher rate analysis reopt. ($\times 2$)
- Total gain - $\times 14$ per hour of data taking

Expect to reach $\sim 10^{-11}$/evt by 2004

E949 Upgrades

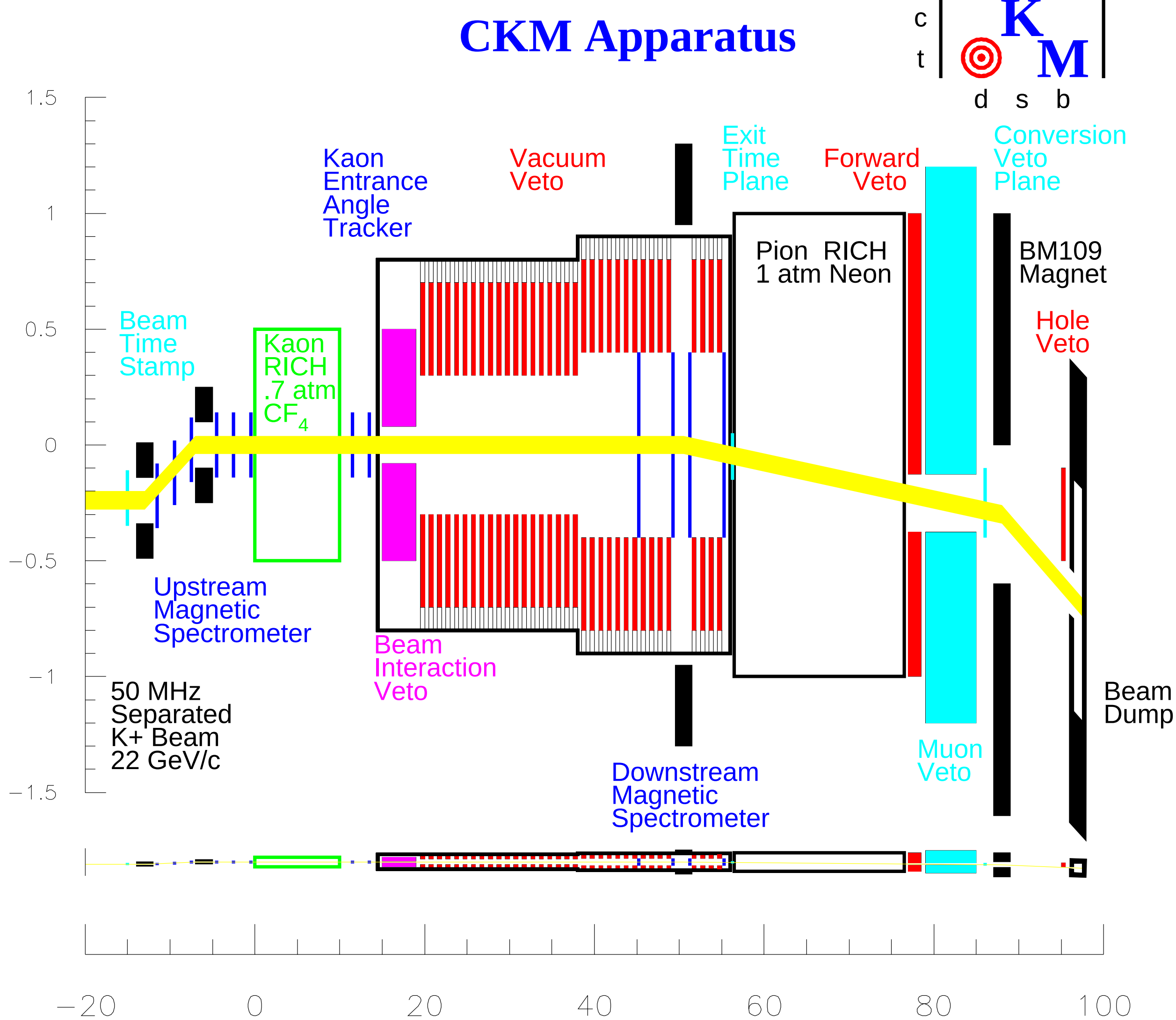
- Realizes full flexibility of the AGS
- 6.5×10^{13} protons/spill to increase duty factor and lower kaon momentum
- Proven technique and background rejection from E787.
- Detector and beam upgrades to improve efficiency and bkg rej.
- Beam upgrades to improve reliability and cope with large flux



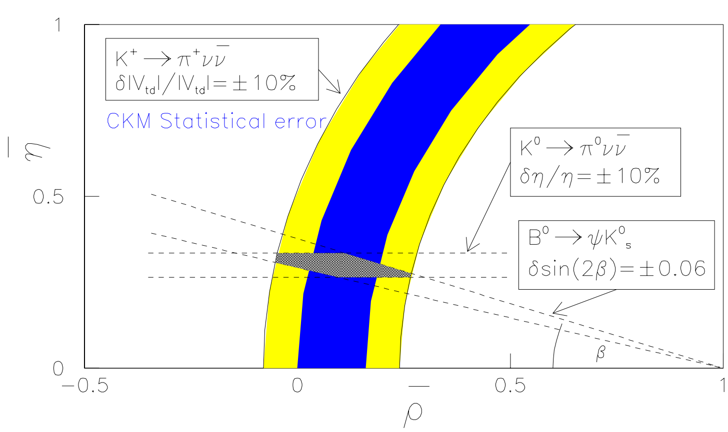
- Photon Veto (access low p_π phase space)
  - Barrel Veto Liner (additional 2.3 $X_\circ$) *Completed*
  - Live degrader upgrade 7/01
  - Additional upstream vetoes 7/01
  - Thicken collar counter 7/01
  - Downstream veto *Completed*
- UTC (tracking efficiency increase) *Completed*
- Range stack upgrades
  - Replace T-counters (better trigger, tracking efficiency) *Completed*
  - Replace Layer 2-5 (better dE/dx resolution, timing) *Completed*
  - Repair dead RSSCs (better tracking efficiency) *Completed*
  - Upgrade RSSC electronics (muon rejection) 9/01
  - Monitor system (reliability and energy resolution)
    - LEDs on RS *Completed*
    - Voltage monitor 8/01
- Trigger upgrade (reduce deadtime and improve rejection) 8/01
- DAQ upgrade (reduce deadtime, increase rate capability) *Completed*
- Beam counter upgrade (increase background rejection) 7/01
- Separator Upgrade *Completed*
- New targets 7/01, ongoing

CKM Experiment to Measure $K^+ \to \pi^+ \nu \bar{\nu}$

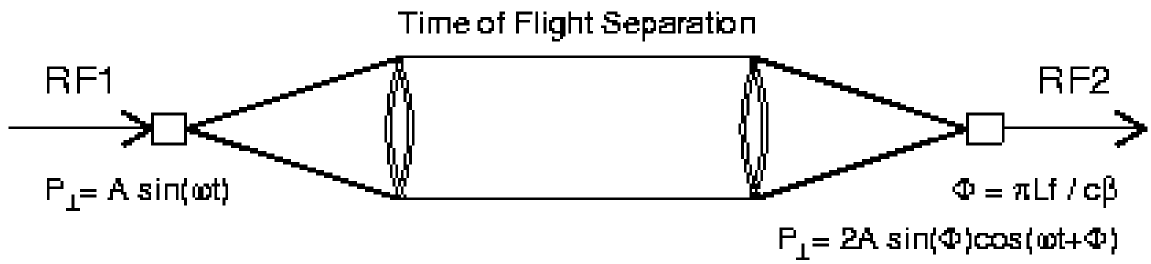
New, in-flight technique:



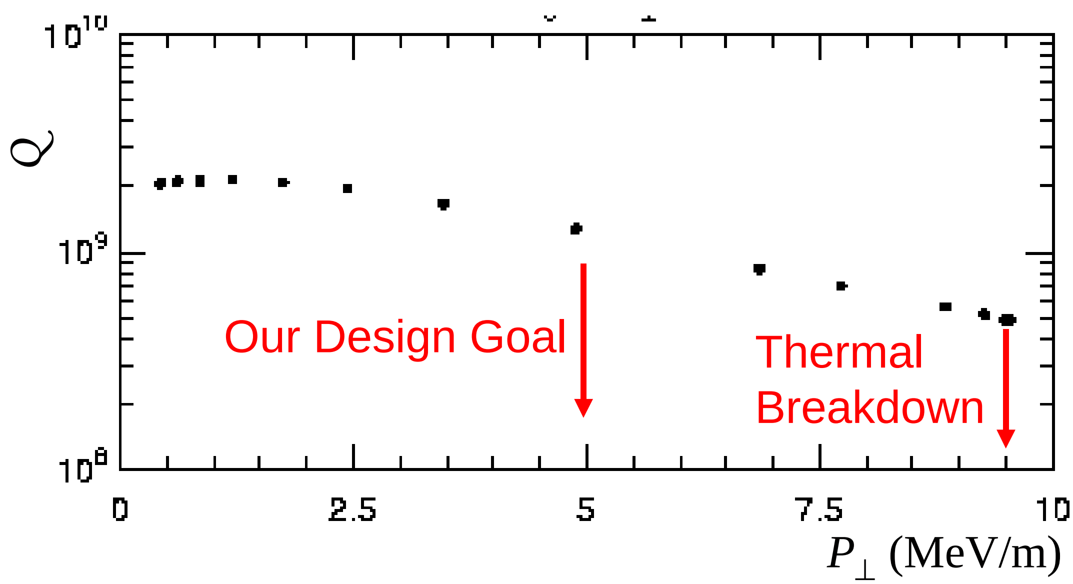
Reach for ~ 100 events:



RF separated K⁺ beam



A recent 1-cell test result:

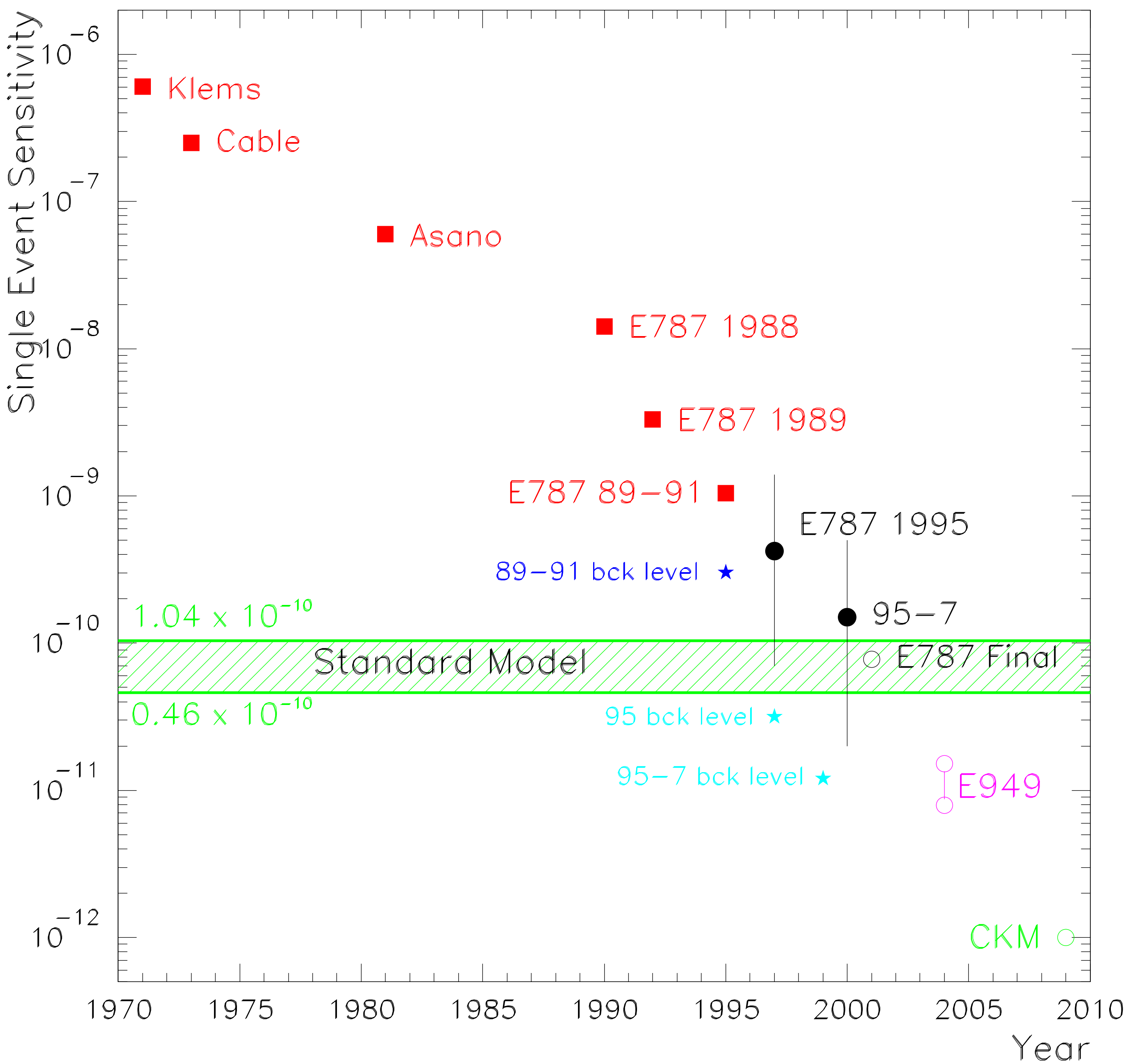


Expressed as B_{MAX} on inner Nb surface:

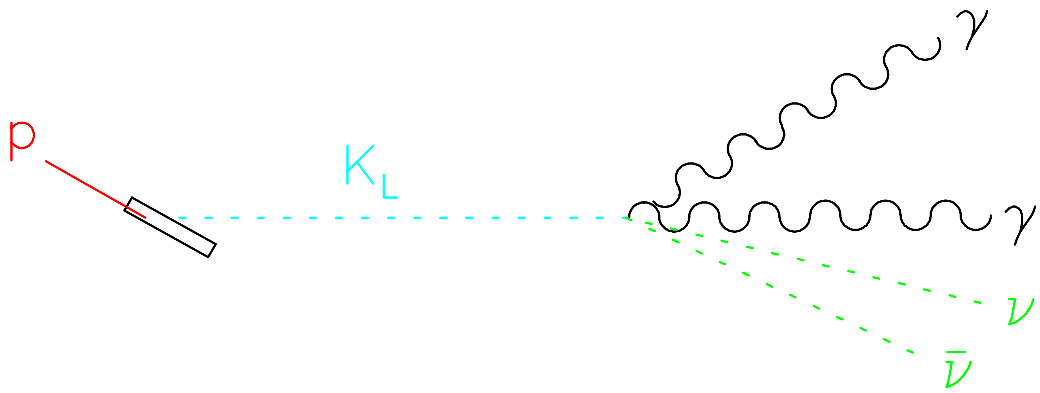
This result:	104mT
Our design @ 5MeV/m:	77mT
TESLA @25 MeV/m:	110mT
TESLA @35 MeV/m:	160mT

Progress in $K^+ \to \pi^+\nu\bar{\nu}$

- E787 observed 1 event in 1995 run
- Analysis of 1995-7 data shows background rejection adequate for measurement at the S.M. level.
- Data collected in 1998 equal in sensitivity to previous total.
- Full E787 data sample (1995–98) will reach S.M. level.
- E949 should reach $\mathcal{O}(10^{-11}/\mathrm{evt})$ with ~ 10 S.M. events
- CKM proposes to reach $\mathcal{O}(10^{-12}/\mathrm{evt})$ by ~ 2010



$K_L \to \pi^0 \nu \bar{\nu}$ experimental issues



All neutral initial & final state, γ's make π^0

Expected branching ratio 3×10^{-11}

- need high flux of K_L

Largest background $K_L \to \pi^0 \pi^0$, BR $\sim 10^{-3}$

- need excellent vetoing, other handles if possible

Background from neutron-produced π^0's, η's

- requires vacuum of 10^{-7}
- need to make sure decay vertex was in beam

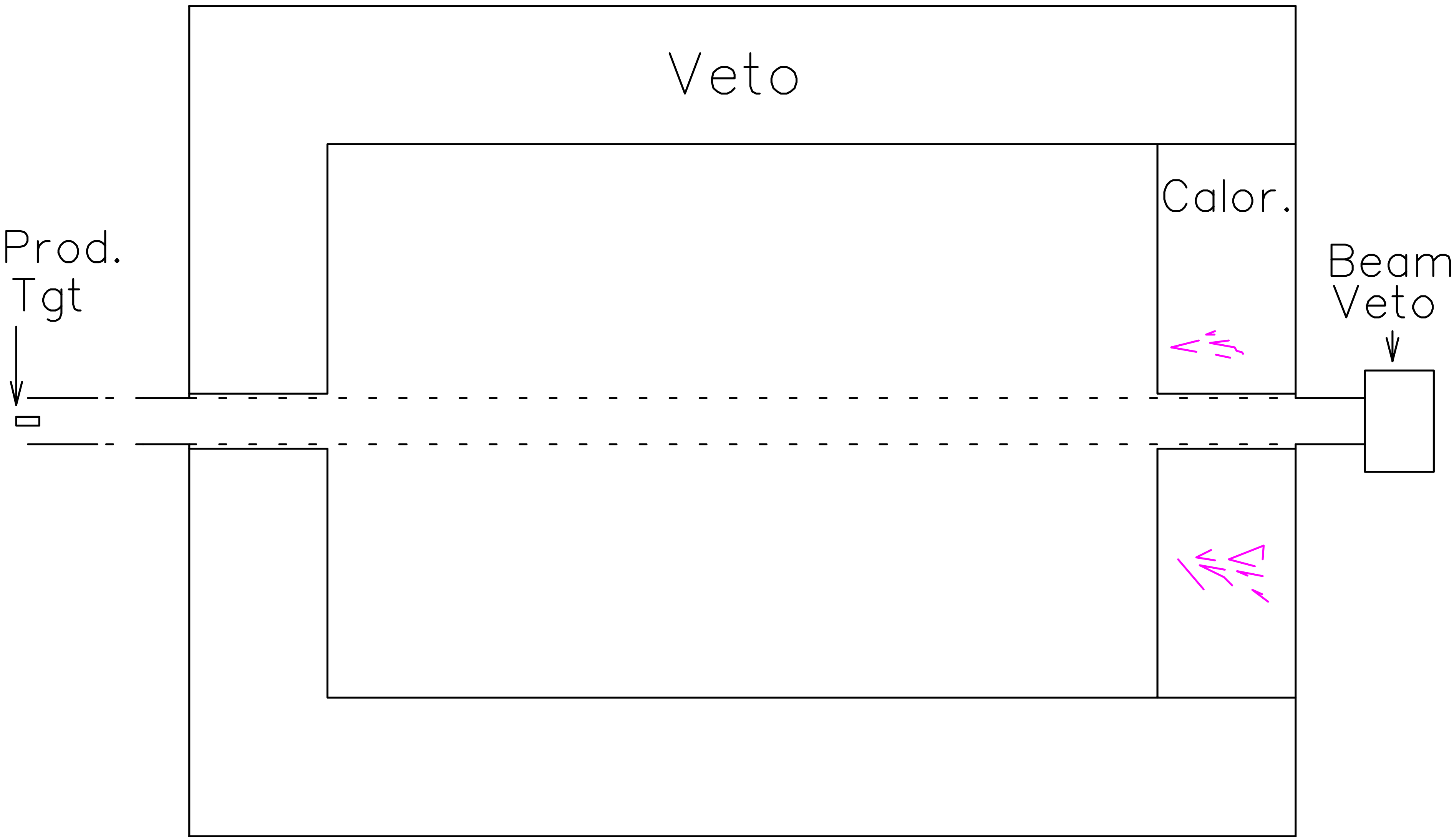
Potential backgrounds from hyperon decay π^0's

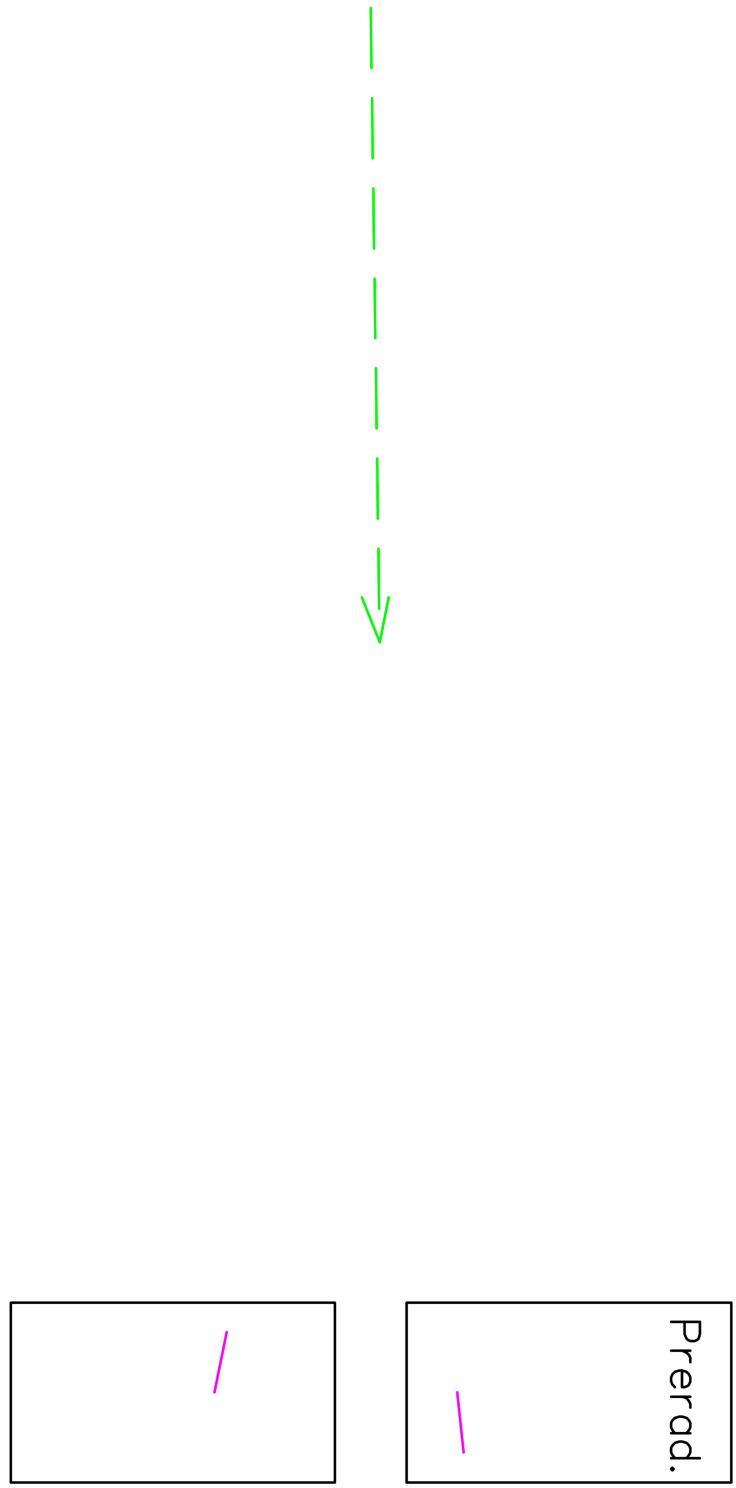
- could use a clever way of getting rid of them

Present status: $B(K_L \to \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$

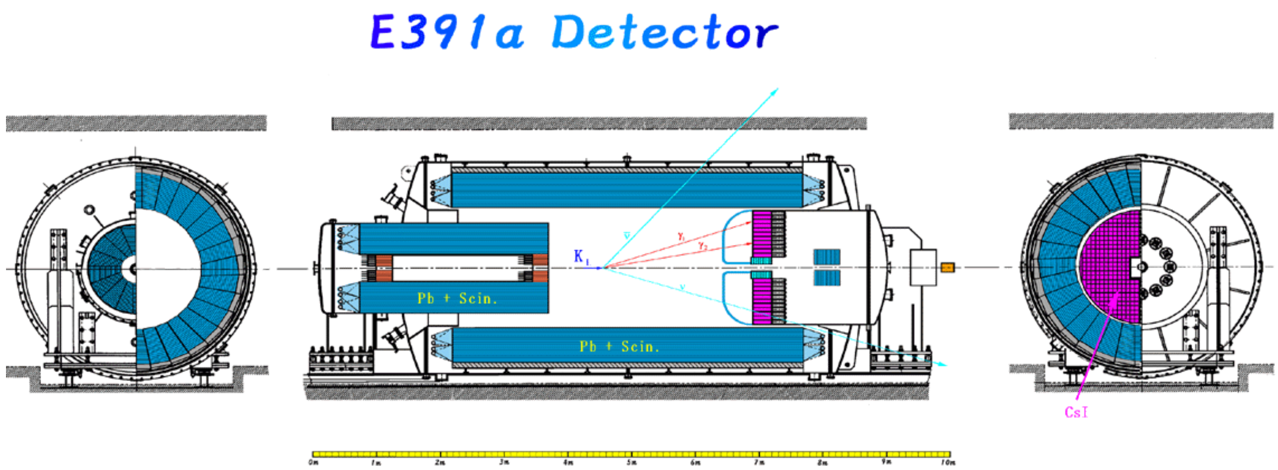
- from KTeV, using Dalitz-converted π^0's

$K_L \to \pi^0 \nu \bar{\nu}$ Experiment




Prerad.

KEK E391a search for $K_L \to \pi^0 \nu \bar{\nu}$



Carefully designed "pencil" beam, compact detector

Entire apparatus in vacuum

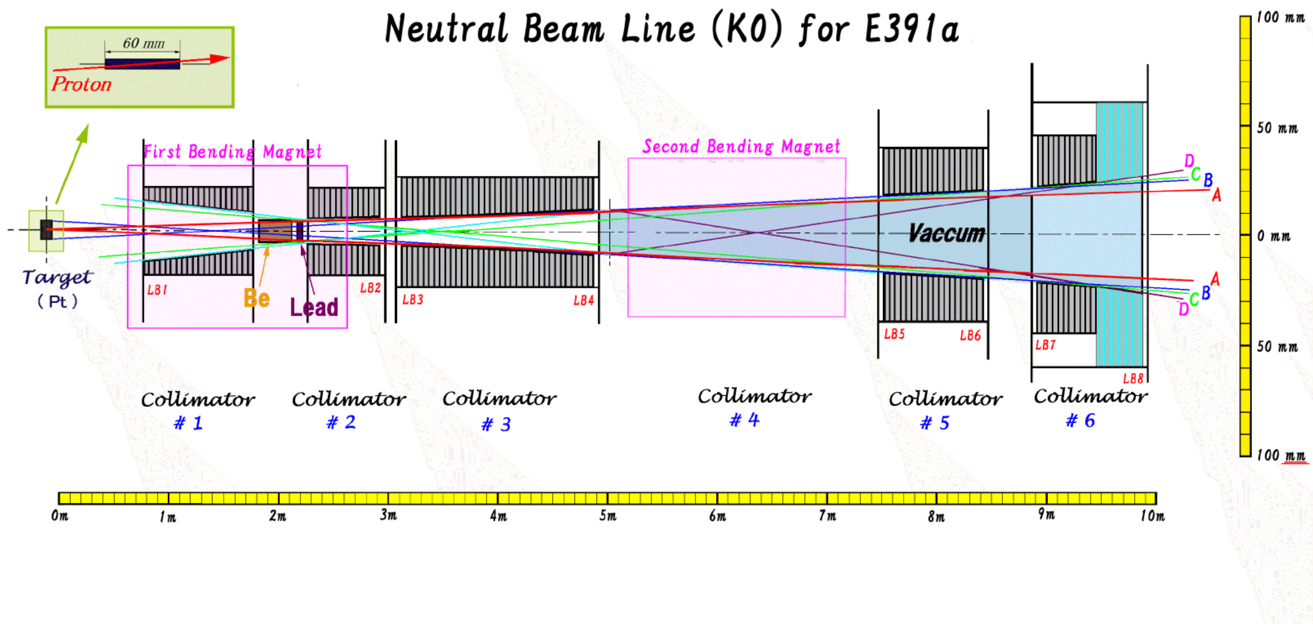
Very high performance photon veto

Expected to reach $\sim 3 \times 10^{-10}$ single event sensitivity
- *i.e.* w/i an order of magnitude of S.M. prediction

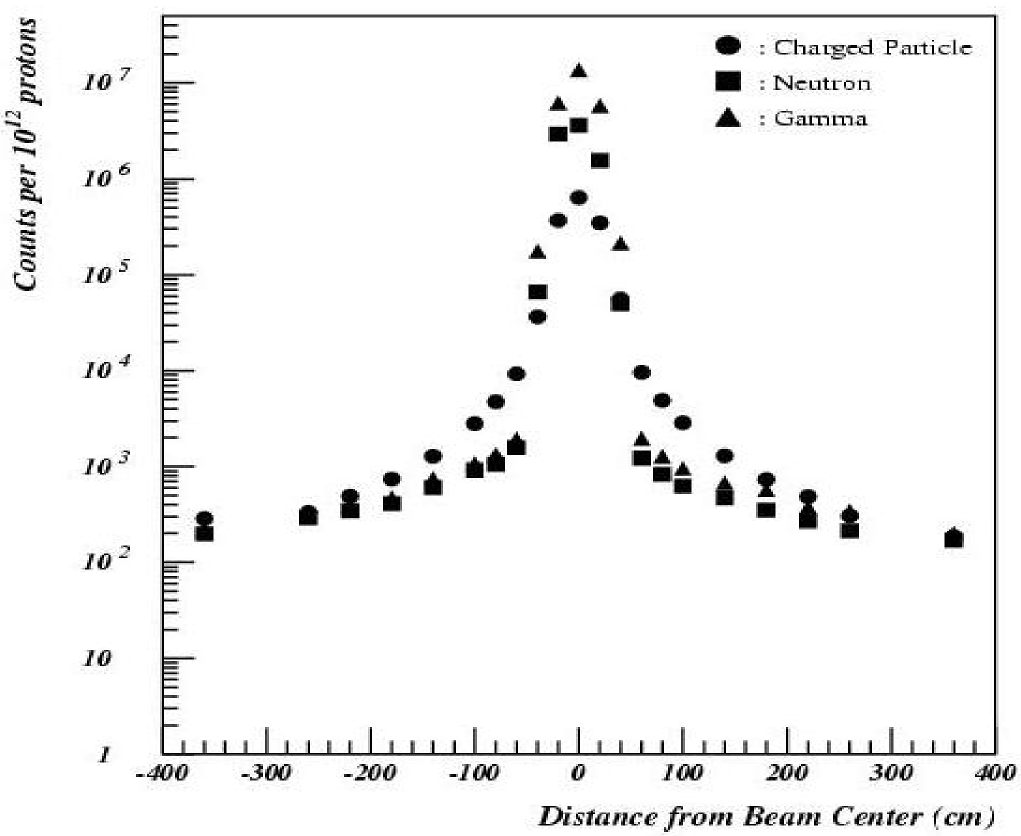
Beamline construction & tuning begun in March 2000

Run start scheduled for Fall, 2003

Test bed for JHF experiment



Critical to reduce the beam halo. Tests encouraging



KaMI $K_L \to \pi^0 \nu \bar{\nu}$

Recent proposal

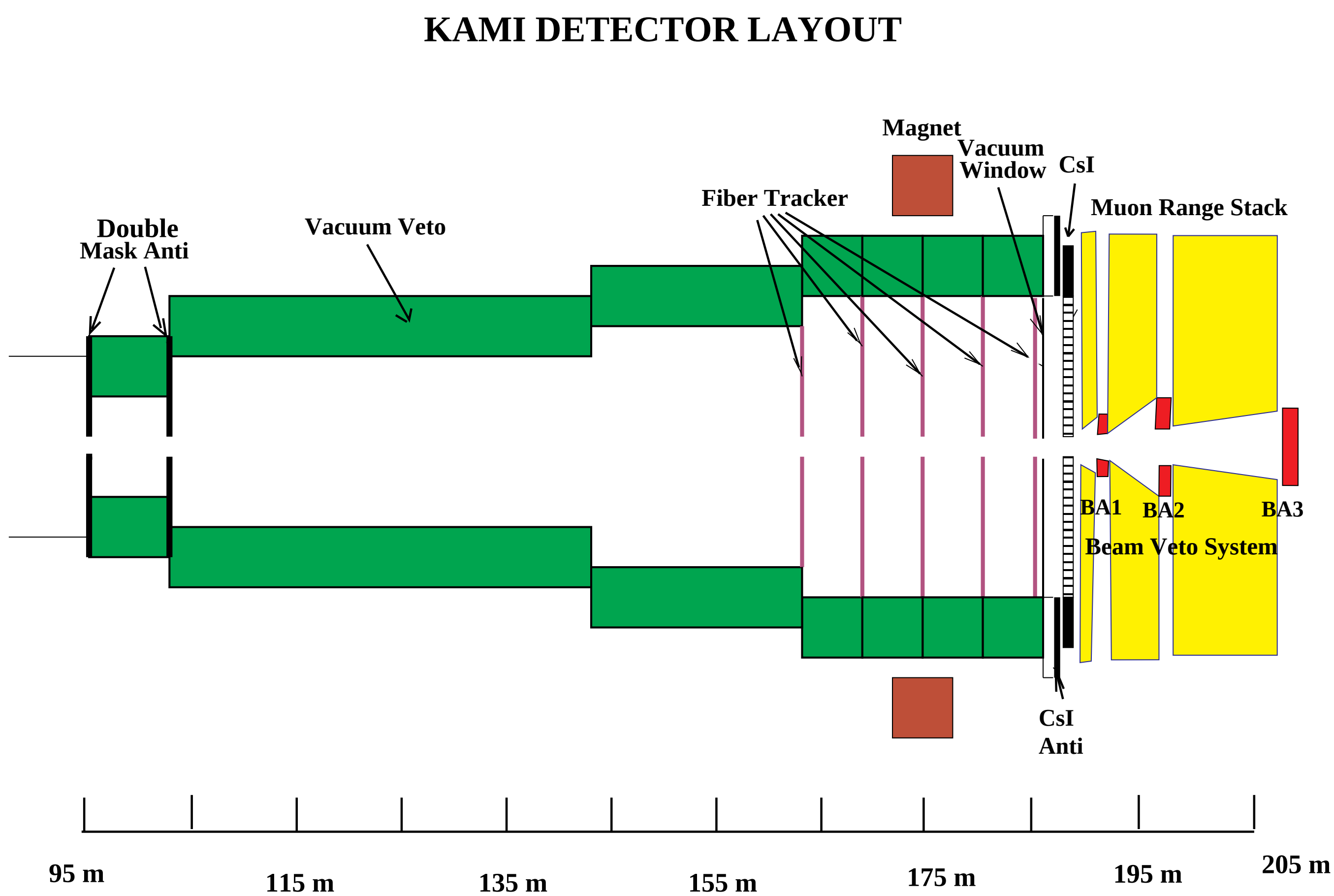
3×10^{13}/spill, 120 GeV proton beam at Main Injector.

Pencil beam, $\pi^0 \to \gamma\gamma$ decay

Recycled KTeV CsI array central, augmented with new modules

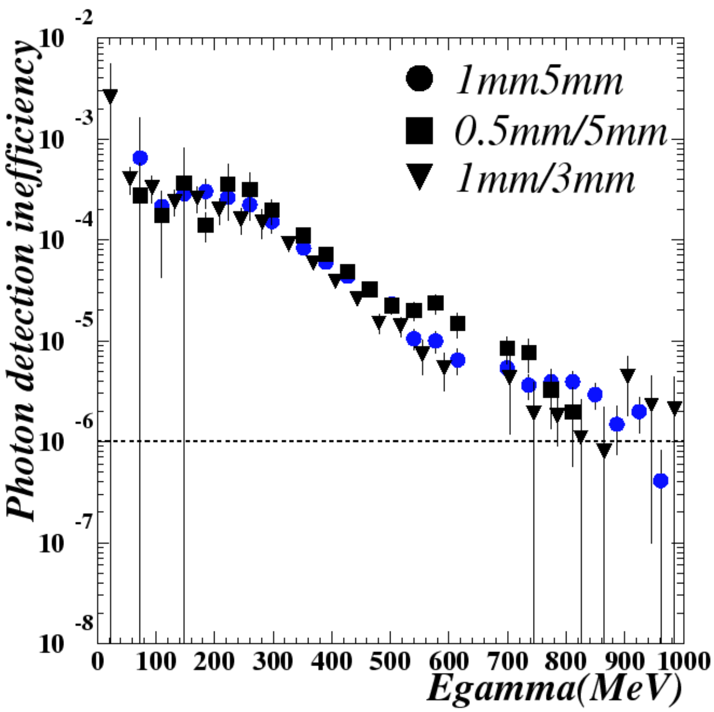
Hermetic veto with extremely low inefficiency

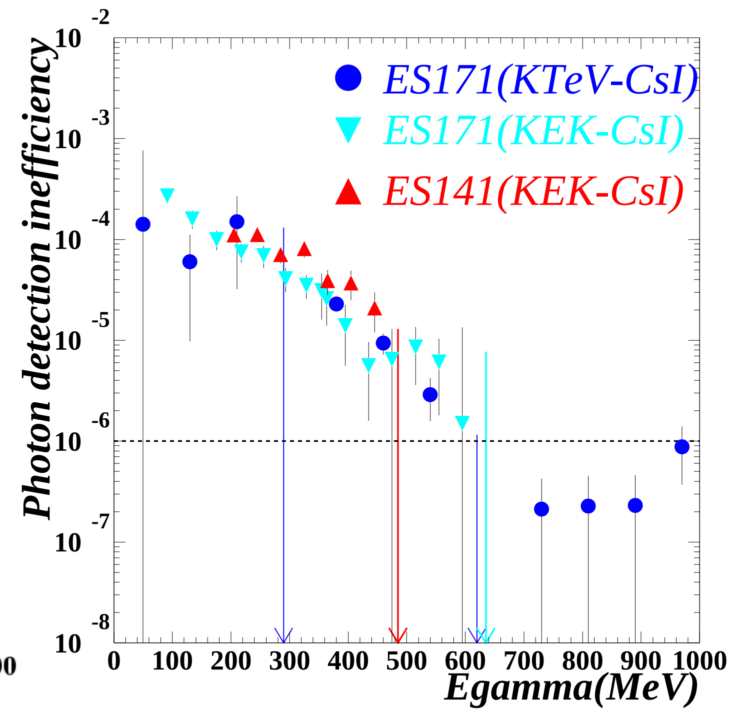
~ 90 events, S:B $\sim 4:1$



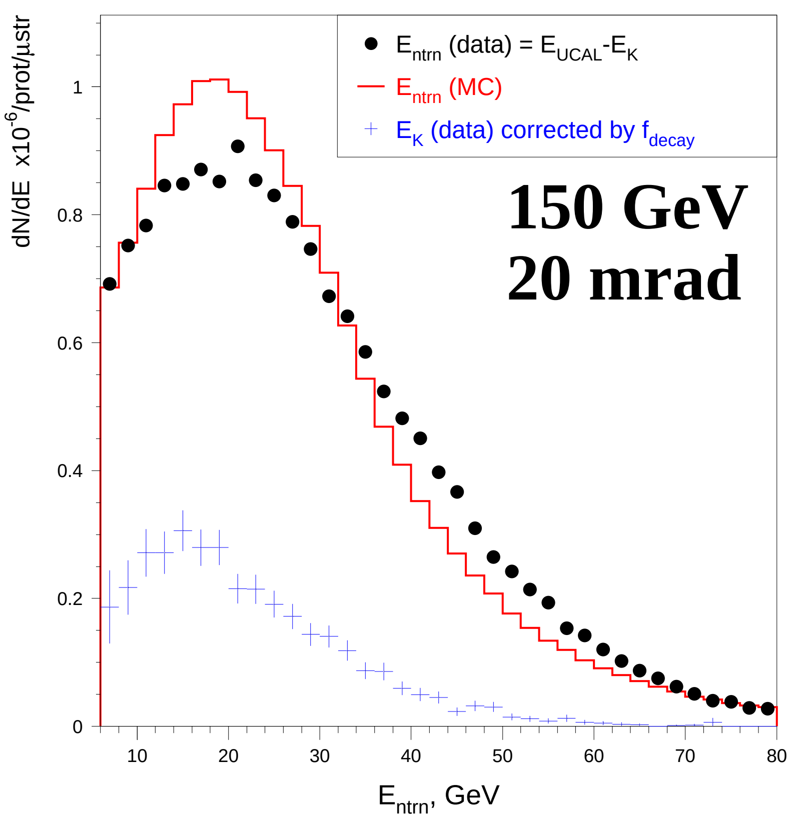
KaMI Progress

Tagged beam tests in Japan suggest extremely low γ inefficiency is achievable.





Main Injector neutron flux measured:



KOPIO $K_L \to \pi^0 \nu \bar{\nu}$

Proposal recommended by National Science Board
- awaiting funding

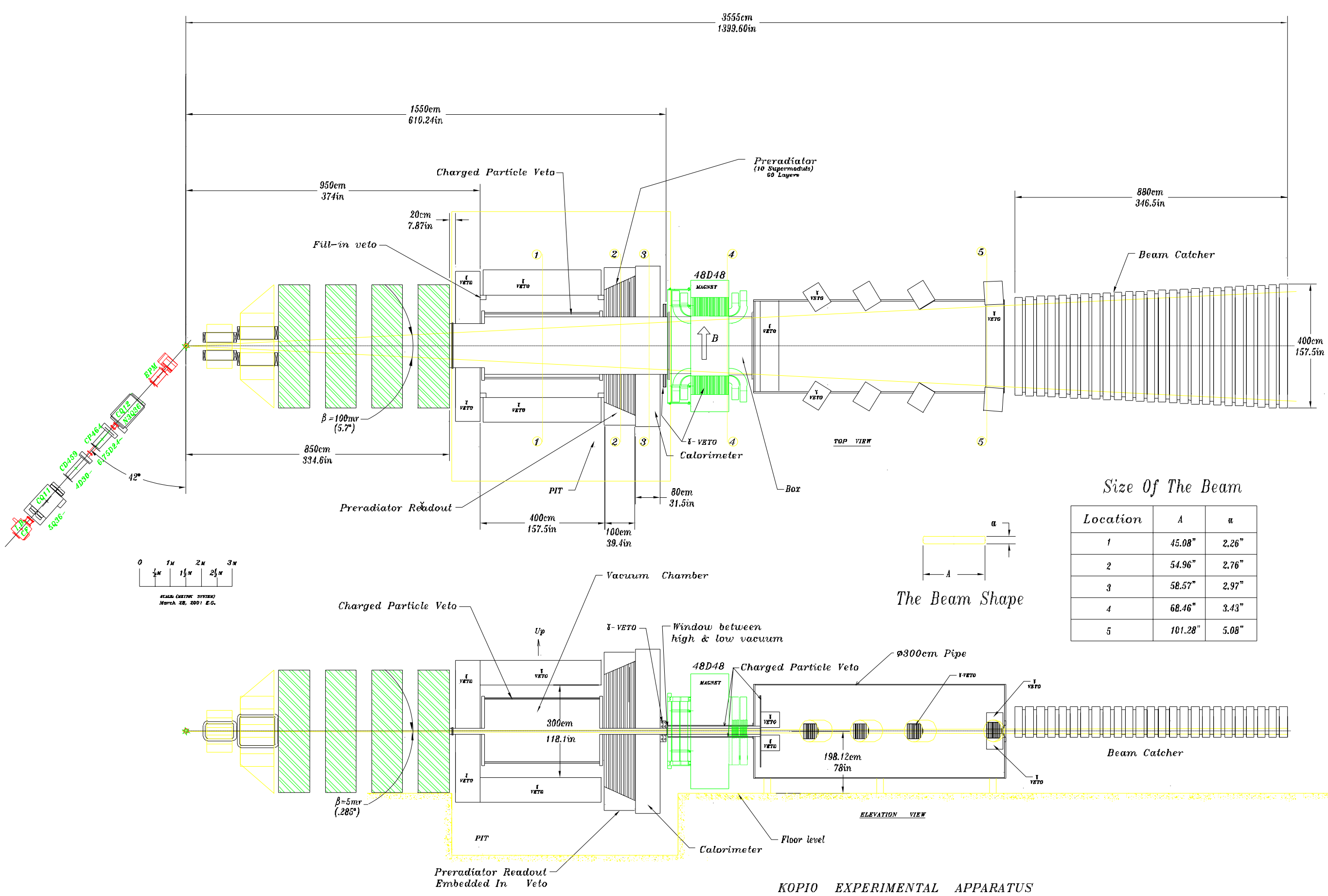
Uses the BNL AGS ~ 20 hrs/day it's not serving RHIC

Microbunched, low energy beam allows TOF determination of p_K

Measures photon direction as well as energy, time, position

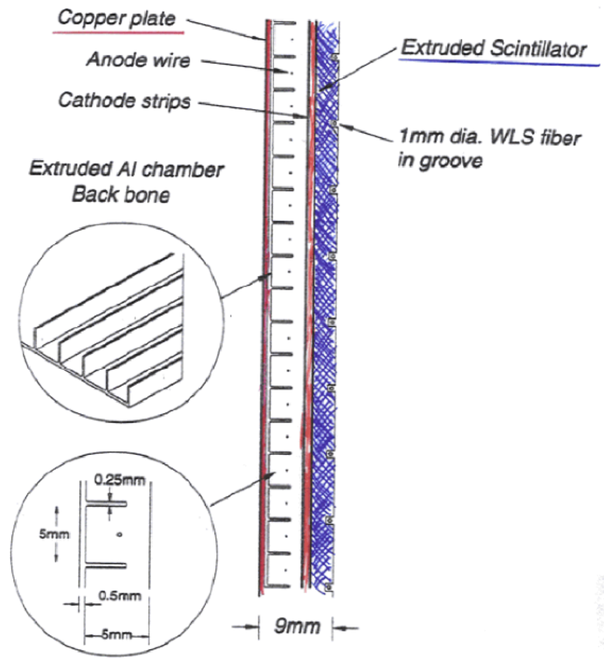
Hermetic veto with proven level of inefficiency

~ 50 events, S:B $\sim 2:1$



Photon angle measurement

Principle: track 1st converted pair
in low-density preradiator

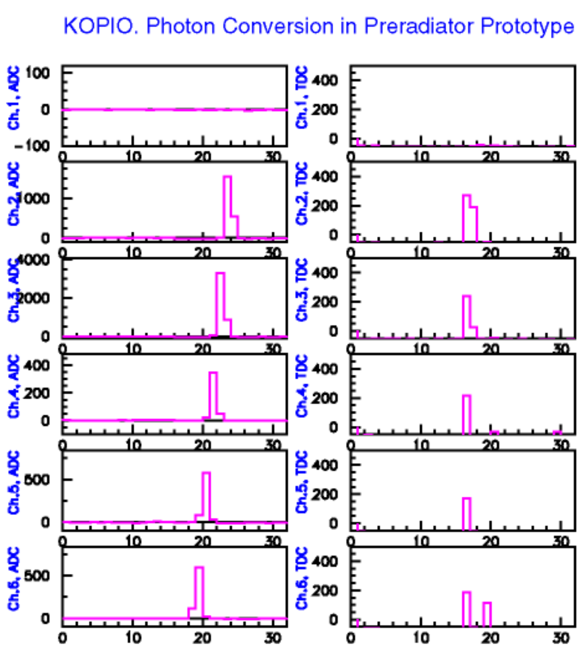


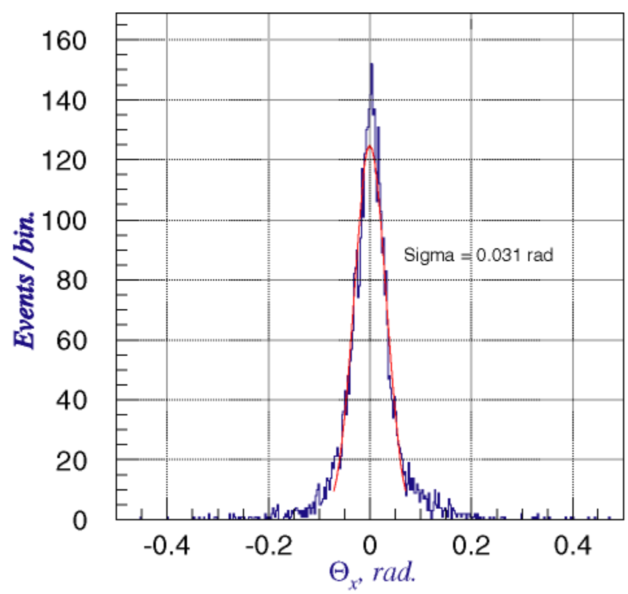
64 layers of chamber + scintillator
- each station $0.03X_0$

We will need $\sigma_\theta \sim 30$mr

MC indicates this can be done

Prototype tests in the LEGS tagged γ beam at the BNL NSLS confirmed this:





Θ_x distribution of detected photons. $E_\gamma = 150$ MeV.

$K_L \to \pi^0 \ell^+ \ell^-$

These decays also sensitive to $Im V_{ts}^* V_{td}$

At first sight much more tractible than $K_L \to \pi^0 \nu \bar{\nu}$

But they suffer from a number of problems, both experimental and theoretical

In addition to $B\left(K_L \to \pi^0 \ell^+ \ell^-\right)_{dir}$ there are 3 problematical contributions:

1. Background from $K_L \to \gamma\gamma\ell^+\ell^-$
   $\sim 10^{-5}\times$ larger than $K_L \to \pi^0 \ell^+ \ell^-$
   Even with very good resolution very hard to fight,
   already seems to be appearing in signal boxes

2. CP-conserving 2γ-mediated state
   Roughly comparable in size to CP-violating piece
   Information on $K_L \to \pi^0 \gamma\gamma$ relevant
      New data from NA48
   But not so easy to make the connection
   F. Gabbiani & G. Valencia hep-ph/01005006
      absorptive contribution model dependent
      + large uncertainty in dispersive contribution

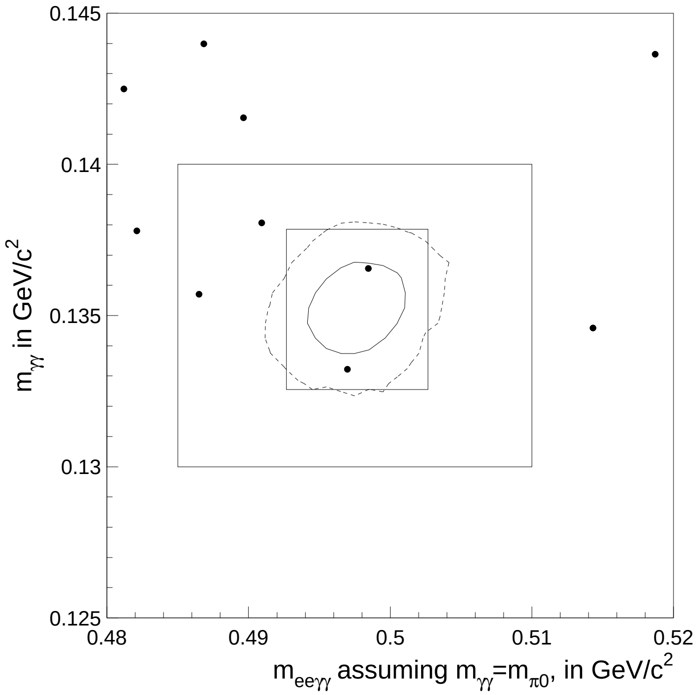
3. State-mixing CP-violating contribution $\propto |\epsilon|^2 B\left(K_S \to \pi^0 \ell^+ \ell^-\right)$
   Best knowledge is of $B\left(K_S \to \pi^0 e^+ e^-\right)$, $< 1.6 \times 10^{-7}$ (NA48)
   This yields $B\left(K_L \to \pi^0 e^+ e^-\right)_{indir} < 4.8 \times 10^{-10}$
   Still probably $100\times$ larger than actual effect
   To make life even more interesting, there's interference

Is there a way out of this morass?

KTeV $K_L \to \pi^0 \ell^+ \ell^-$

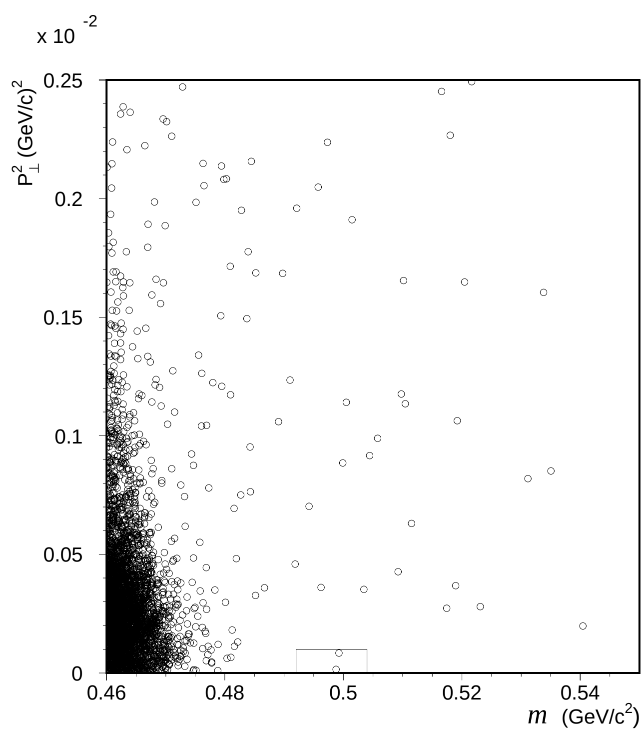
$B(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$

Main background:
$K_L \to \gamma\gamma e^+ e^-$



$B(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$

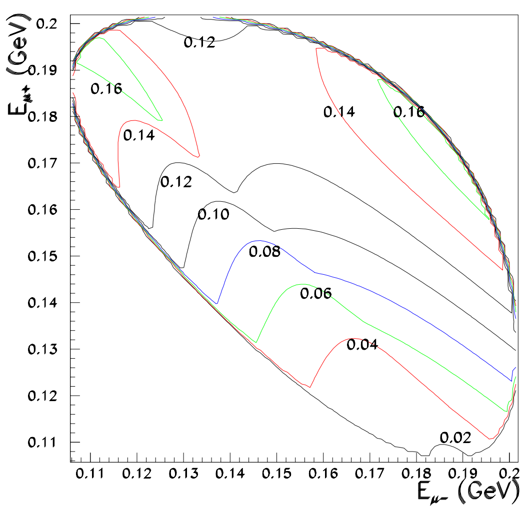
Main backgrounds:
$K_L \to \gamma\gamma\mu^+\mu^-$
$K_L \to \pi^0\pi^+\pi^-$
$K_L \to \pi^\pm\mu^\mp\nu\ +\ 2$ accid γ



Near term prospect: $\sim 2.5\times$ more data
- but background already closing in.

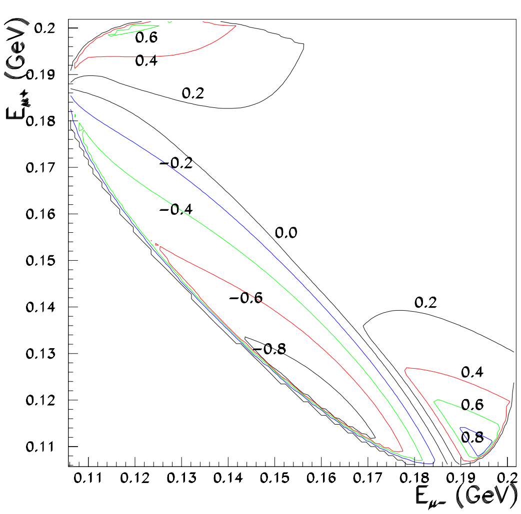
$\pi^0\mu^+\mu^-$ Summary

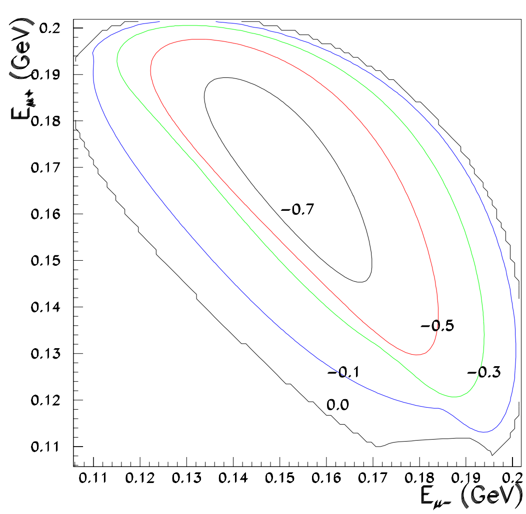
- The parity-odd observable P_L has the interesting property of being sensitive to Direct-CPV.
- Both out-of-plane polarization and the lepton energy asymmetry are sensitive to indirect CP.
- Could all three measurements and the branching ratio be used to obtain the direct component ?
- Still need to examine how well the decay is described in terms of a_s, α_V, and $Im(\lambda_t)$.



Decay distribution

Longitudinal and out-of-plane polarizations





Conclusions

LFV experiments have been pushed to remarkable sensitivities
- correspond to mass scale of well over 100 TeV

But success has killed most models predicting LFV in K decay
- future mainly as by-products of other studies

High precision measurement of $K_L \to \mu^+\mu^-$ available
- very useful if theoretical issues resolved
- auxilliary measurements to help this resolution in process
- but situation still unsettled

$K_L \to \pi^0\ell^+\ell^-$ experiments have been pushed by an O.M.
- Experiments on auxillary processes have made similar progress
- But background is starting to be seen
- and progress in untangling the components slow
- Maybe new idea will help

$K^+ \to \pi^+\nu\bar{\nu}$ has been seen,
- clear that it can be exploited
- two initiatives to pursue it further
  - 10^{-11}/evt level experiment in testing stage
  - 10^{-12}/evt level experiment in R&D phase

First dedicated experiment to seek $K_L \to \pi^0\nu\bar{\nu}$ proceeding
Two other initiatives in progress
- trying for $\sim 10\%$ measurement of η

Goal is future high precision determinations of λ_t from K's
to be compared to B information to critically test SM